

2019-06

Cadmium and/or copper excess induce interdependent metal accumulation, DNA methylation, induction of metal chelators and antioxidant defences in the seagrass *Zostera marina*

Greco, M

<http://hdl.handle.net/10026.1/13334>

10.1016/j.chemosphere.2019.02.123

Chemosphere

Elsevier

All content in PEARL is protected by copyright law. Author manuscripts are made available in accordance with publisher policies. Please cite only the published version using the details provided on the item record or document. In the absence of an open licence (e.g. Creative Commons), permissions for further reuse of content should be sought from the publisher or author.

Accepted Manuscript

Cadmium and/or copper excess induce interdependent metal accumulation, DNA methylation, induction of metal chelators and antioxidant defences in the seagrass *Zostera marina*



Maria Greco, Claudio A. Sáez, Rodrigo A. Contreras, Fernanda Rodríguez-Rojas, M. Beatrice Bitonti, Murray T. Brown

PII: S0045-6535(19)30347-9

DOI: 10.1016/j.chemosphere.2019.02.123

Reference: CHEM 23235

To appear in: *Chemosphere*

Received Date: 15 November 2018

Accepted Date: 19 February 2019

Please cite this article as: Maria Greco, Claudio A. Sáez, Rodrigo A. Contreras, Fernanda Rodríguez-Rojas, M. Beatrice Bitonti, Murray T. Brown, Cadmium and/or copper excess induce interdependent metal accumulation, DNA methylation, induction of metal chelators and antioxidant defences in the seagrass *Zostera marina*, *Chemosphere* (2019), doi: 10.1016/j.chemosphere.2019.02.123

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Cadmium and/or copper excess induce interdependent metal accumulation, DNA methylation, induction of metal chelators and antioxidant defences in the seagrass *Zostera marina*

Maria Greco^{1,2}, Claudio A. Sáez^{3,5*}, Rodrigo A. Contreras⁴, Fernanda Rodríguez-Rojas³, M. Beatrice Bitonti², Murray T. Brown^{5*}

¹ *The Francis Crick Institute, London, United Kingdom.*

² *Dipartimento di Biologia, Ecologia e Scienze della Terra, Università della Calabria, Arcavacata di Rende, Italy.*

³ *Laboratory of Aquatic Environmental Research, Centro de Estudios Avanzados, Universidad de Playa Ancha, Viña del Mar, Chile.*

⁴ *Laboratory of Plant Physiology and Biotechnology, Departamento de Biología, Facultad de Química y Biología, Universidad de Santiago de Chile, Santiago, Chile. Current address: The Not Company, Macul, Santiago, Chile.*

⁵ *School of Biological and Marine Sciences, Faculty of Science and Engineering, University of Plymouth, Plymouth, United Kingdom.*

*Corresponding authors: claudio.saez@upla.cl

mtbrown@plymouth.ac.uk

Abstract

In this investigation, we assessed the effects of Cu and/or Cd excess on physiological and metabolic processes of the widespread seagrass *Zostera marina*. Adult were exposed to low Cd and Cu (0.89 and 0.8 μM , respectively) and high Cd and Cu (8.9 and 2.4 μM , respectively) for 6 d at: Control conditions; low Cu; high Cu; low Cd; high Cd; low Cd and low Cu; and high Cd and high Cu. Photosynthetic performance decreased under single and combined treatments, although effects were more negative under Cu than Cd. Total Cu accumulation was higher than Cd, under single and combined treatments; however, their accumulation was generally lower when applied together, suggesting competition among them. Levels of glutathione (GSH) and phytochelatins (PCs) followed patterns similar to metal accumulation, with up to PC5, displaying adaptations in tolerance. A metallothionein (*MET*) gene showed upregulation only at high Cd, low Cu, and high Cu. The expression of the enzymes glutathione reductase (*GR*), ascorbate peroxidase (*APX*), and catalase (*CAT*) was greatest at high Cu, and at high Cd and Cu together; the highest expression was under Cu, alone and combined. Both metals induced upregulation of the DNA methyltransferases *CMT3* and *DRM2*, with the highest expression at single Cu. The DNA demethylation *ROS1* was overexpressed in treatments containing high Cu, suggesting epigenetic modifications. The results show that under copper and/or cadmium, *Z. marina* was still biologically viable; certainly based, at least in part, on the induction of metal chelators, antioxidant defences and methylation/demethylation pathways of gene regulation.

Keywords: epigenetics; marine angiosperm; metal tolerance; photosynthesis; mechanism.

1. Introduction

Seagrasses are a small group of monocotyledonous angiosperms that re-colonised the seas, on at least three separate occasions, from around 100 Mya (Dittami et al. 2017). They now occupy soft sedimentary substrata in shallow coastal-waters and estuaries where they can form dense meadows that have important ecological roles and provide a range of ecosystem services (Nordlund et al. 2016). However, they are under threat from biotic and abiotic stresses, including from multiple anthropogenic pressures, that is leading to a global decline in their coverage estimated to be about 7% per annum (Waycott et al. 2009). Proximity to industrial activities and urban development exposes seagrasses to inputs of organic and inorganic chemicals from both point and diffuse sources. While the impacts by organic pollutants may be transitory, the environmental persistence of metals, their accumulation from both water column and sediments and transfer to higher trophic levels are likely contributors to the long-term decline in the health of seagrass meadows (Barwick and Maher 2003, Zheng et al. 2018). Although information on metal toxicity is limited, there are reports of reduced growth rates and impaired photosynthetic performance in a few seagrass species when exposed to metals such as cadmium (Cd), copper (Cu), lead (Pb) and zinc (Zn) (Macinnis-Ng and Ralph 2002, 2004, Zhao et al. 2006, Ambo-Rappe et al. 2011). Cd and Cu are two of the most widely naturally occurring metals in marine environments, but inputs from anthropogenic sources have altered their natural cycling and, as a consequence, their bioavailability to marine biota has increased (Coelho et al. 2013). Cu is an essential micronutrient with structural and catalytic roles, as components of proteins and enzymes involved in various metabolic pathways and physiological processes, but can be toxic beyond certain threshold concentrations (Yruela 2005). Cd is a non-essential metal with no known function in plants and animals (Deckert 2005, Park et al.

2008). Toxic concentrations of Cu and Cd can affect several physiological processes and biochemical events such as growth, photosynthesis, cell respiration, biosynthesis of chlorophyll and protein, DNA replication and enzyme activities (Sandalio et al. 2001, Romero-Puertas et al. 2002, Shukla et al. 2003). In this context, it has been proposed that epigenetic modifications that modulate transcriptionally silent or active chromatin by reversible methylation/demethylation processes, may be involved in abiotic stress responses, including metal tolerance in several plant species (Aina et al. 2004, Choi and Sano 2007, Lukens and Zhan 2007, Boyko and Kovalchuk 2008, Greco et al. 2012, 2013, Ding et al. 2014). In plants, cytosine methylation is promoted by three families of DNA methyltransferases: DMT1, DRMs and CMTs (Bartels et al. 2018), while DNA demethylation is addressed by the enzymatic removal of the methylated cytosine initiated by ROS1/DME family (Li et al. 2017). For instance, there is evidence of Cd-induced DNA hypermethylation in radish (Yang et al. 2007), *Arabidopsis thaliana* (Li et al. 2015, Wang et al. 2016), rice (Feng et al. 2016), and also in the seagrass *Posidonia oceanica* (Greco et al. 2012). In contrast, the red seaweed *Gracilaria dura* displayed severe cytosine demethylation under Cd exposure (Kumar et al. 2012). Cu exposure has also led to variations in DNA methylation patterns in red maple (Kalubi et al. 2017), and the aquatic herb *Hydrilla verticillata* (Shi et al. 2017).

The main pathway by which metals such as Cd and Cu induce biological stress is the induction of an oxidative stress condition, mainly caused by the overproduction of reactive oxygen species (ROS) through the disruption of electron transport chains and excess energy transfer to oxygen in chloroplasts and mitochondria (Fryzova et al. 2018). It is widely acknowledged that the “Foyer-Halliwell-Asada” pathway, based on *de novo* synthesis and recycling of the antioxidants glutathione (GSH) and ascorbate (ASC), is the main

mechanism to counteract ROS excess in plants. The process is mediated by the activities of several enzymes, among which are ascorbate peroxidase (APX), glutathione reductase (GR), and dehydroascorbate reductase (DHAR) (Foyer and Noctor 2011). Other enzymes, such as catalase (CAT) and superoxide dismutase (SOD), also contribute in decomposing ROS, specifically hydrogen peroxide (H_2O_2) and superoxide anions ($\bullet O_2^-$), respectively (Foyer and Noctor 2011). For example, with exposure of up to 70 μM Cd for 6 d, GSH concentrations increased in the seagrass *Thalassia testudinum*, and in *Zostera japonica* exposure to 50 μM Cd or Cu for 7 d resulted in increased activities of SOD and CAT (Lin et al. 2016). In response to metal toxicity, plants activate different mechanisms that include detoxification by the binding of metals to ligands (Pal et al. 2018). Metal chelation represents a first line of defence for cells against internalized metals. Free metals are complexed in the cytosol by different chelators to reduce their bioavailability and facilitate their sequestration away from sensitive sites (Seth et al. 2012). These ligands include amino acids, organic acids, the tripeptide glutathione (GSH) and the metal-binding peptides phytochelatins (PCs) and metallothioneins (MTs) (Guo et al. 2008, Verbruggen et al. 2009, Foyer and Noctor 2011). PCs are a family of cysteine-rich peptides, with a general structure $(\gamma\text{-Glu-Cys})_n\text{-Gly}$ ($n = 2$ to 11), that are synthesised from reduced GSH by the enzyme phytochelatin synthase (PCS) (Cobbett and Goldsbrough 2002). Because of the normally high cytosolic GSH concentrations, an influx of metal ions will generate GSH-metal complexes that are rapidly converted into PCs by the constitutively expressed PCS. Cd is considered the best activator of PCs (Clemens 2006), but other metals (e.g. Cu, Zn, As, Hg, Pb) can also do so (Cobbett 2000). A recent study by Nguyen et al. (2017) reported the occurrence of PC2 and PC3 in the roots of the seagrass *Enhalus acoroides* growing in highly Pb-contaminated sites in Vietnam but, to the best of our knowledge, the presence of

specified PCs in seagrasses experimentally exposed to elevated concentrations of metals has not been published previously. However, unspecified non-protein thiols (other than glutathione) and phytochelatin-(PC)-like peptides have been identified in leaves of *P. oceanica* and *T. testudinum*, respectively, on exposure to Cd (Maserti et al. 2005).

METs are cysteine-rich polypeptides but unlike PCs, MT proteins are encoded by a family of genes. Consequently, a set of MET isoforms can exist that can be species- and metal-specific (Cobbett and Goldsbrough 2002, Leitenmaier and Küpper 2013). METs are found in many groups of organisms including plants, but evidence for their involvement in mediating metal tolerance, distribution and accumulation in plants is limited (e.g. Li et al. 2013, Liu et al. 2014). So far, three genomic sequences putatively encoding type-II *METs* (*MET2*) have been isolated from *P. oceanica* (Giordani et al. 2000), and whose expression levels increase under both Cd and Cu excess (Giordani et al. 2000, Cozza et al. 2006).

In this study, we investigated the inter-relationship between physiological, metabolic and transcriptomic processes in the seagrass *Zostera marina* (eelgrass) exposed to single and combined Cd and Cu exposure. Specifically, we measured the maximum quantum yield of PSII (F_v/F_m), a sensitive indicator of photosynthetic performance and thus of plant health (Maxwell and Johnson 2000), concentrations of the intracellular metal-chelators GSH, PCs and, levels of *MT* transcripts, and modulation of genes involved in antioxidant defence and DNA methylation/demethylation. *Zostera marina* was selected because of its widespread distribution in the temperate northern hemisphere of the Atlantic and Pacific Oceans (Bostrom et al. 2014), and sensitivity to environmental perturbations (Ferrat et al. 2003).

2. Materials and methods

2.1. Plant materials and sample preparation

Plants of *Z. marina* were collected from a pristine site in south west England (Salcombe 50°13'30.40"N - 3°46'52.82"W; T°= 14.8°C; salinity= 33 psu; pH = 8.2; O₂ = 8.84 mg L⁻¹), and transported to the laboratory in seawater within 2 h. Plants were rinsed three times with sterilized seawater, all visible epiphytes were removed with a sterile razor blade and then acclimated to laboratory conditions for 2 d in acid-washed 50 L aquaria. Plants were maintained in continuously aerated filtered (0.45 µm) seawater (pH 7.8±0.2), at 15±0.5°C and an irradiance of 45 µmol m⁻²s⁻¹ photosynthetic active radiation (PAR), on a 14/10 h light/dark cycle.

2.2. Metal exposure

Following the acclimation period, 10, similarly sized, adult plants were transferred to 21 individual 2 L aquaria, containing 1.5 L filtered seawater to which Cd and/or Cu was added. The experiment consisted of 7 treatments in triplicate: control (no added metal); Cu (CuSO₄) added at nominal concentrations of either 0.8 µM (50 µg L⁻¹) or 2.4 µM (150 µg L⁻¹), Cd (CdCl₂) at 0.89 µM (100 µg L⁻¹) or 8.9 µM (1000 µg L⁻¹), Cu plus Cd at 0.8 µM Cu and 0.89 µM, respectively, Cu plus Cd at 2.4 and 8.9 µM, respectively. Cu and Cd exposure were selected upon environmentally representative concentrations in polluted environments, and also according to recognized chronic levels in different seagrass species, including *Z. marina* (e.g. Barwick and Maher 2003; Macinnis-Ng et al. 2006; Alvarez-Legorreta et al. 2008; Greco et al. 2012; Lin et al. 2016). Plants were exposed to the treatments for 6 d, with growth media replenished on day 3 in order to avoid depletion of nutrients and metals. At the end of the experiment, leaves from all plants were collected, blotted dry, immediately frozen in liquid nitrogen and stored at -80°C until further biochemical and molecular analyses. Biomass for metal analyses was freeze-dried for 24 h and then stored in a desiccator.

2.3. Determination of photosynthetic performance

Measurements of chlorophyll *a* fluorescence (pulse modulated chlorophyll fluorometer FMS-1, Hansatech Instruments Ltd., Norfolk, England) were taken on leaves ($n=10$) from 3 randomly selected plants from each aquarium prior to the start and at the end of the exposure period. The maximum fluorescence (F_m) of dark adapted leaves (30 min) and minimum fluorescence (F_o) were recorded and the maximum quantum yield of PSII calculated from the ratio of variable to maximum fluorescence (F_v/F_m that is derived from $(F_m - F_o)/F_m$).

2.4. Determination of Cd and Cu content in leaves

Between 30-60 mg of freeze-dried (DW) leaves were digested in a microwave oven (MARSH-press) in 2 mL of HNO_3 as described in Roncarati et al. (2015). After digestion, the volume of each sample was adjusted to 10 mL with milli-Q (18 Ω) water. Total concentrations of each metal were determined using ICP-MS (Thermo Scientific, X Series 2) as in Roncarati et al. (2015). The same methods were applied to certified reference material (IAEA-140; BCR-279); results showed less than 15% variation according to Cu and Cd reference values.

2.5. Analysis of PCs

PCs were detected with modifications from Lavoie et al. (2009). Briefly, 0.2 g FW of leaves were added to 1.2 mL of 0.1% (w/v) trifluoroacetic acid (TFA), containing 6.3 mM diethylenetriamine-pentaacetic acid (DTPA). The mixture was centrifuged at 7,400 g for 20 min at 4°C, and the supernatant recovered. The derivatization of thiol groups with monobromobimane (mBrB) was performed by mixing 250 μ L of the clear homogenate, 450 μ L of 200 mM HEPES pH 8.2, 6.3 mM DTPA, and 10 μ L of 25 mM mBrB (Invitrogen, Oregon, USA); incubation was carried out for 30 min at room temperature in the darkness.

The reaction was stopped with the addition of 300 μ L of 1 M methanesulfonic acid (MSA). Samples were filtered through 0.45 μ m pore size membranes and stored at 4 °C in darkness. PCs were analysed by High Performance Liquid Chromatography (HPLC) using an Agilent 1100 Series system, and data was compiled using Chemstation software. PCs (20 mL extract) were separated on a reversed phase C-18 column (5 μ m particle size, 4.6 mm inner diameter, 15 cm length) at 25°C. Elution was performed using solvent A (0.1% TFA in aqueous solution) and solvent B (100% acetonitrile) with linear gradient (10 min from 0 to 20%, 30 min from 20 to 35%, and 10 min from 35 to 100% of solvent B), and a flow rate of 1 mL min⁻¹. PCs were detected by fluorescence at 380 nm excitation and 470 nm emission wavelengths. Pure PCs standards with degrees of polymerization from n=2 to n=6 (AnaSpec Inc., San Jose, CA, USA) were dissolved in filtered water. Retention times of PC2, PC3, PC4, PC5 and PC6 were 4.4, 11.5, 16.9, 19.9 and 21.6 min, respectively.

2.6. Total RNA extraction and reverse transcription

Total RNA was separately extracted from different leaf samples following the protocol of Doyle (1991) with modifications. All solutions were prepared with RNase-free distilled water. Three hundred grams FW ground biomass were mixed with 0.1 g PVP-40. One mL of freshly prepared extraction buffer ([200 mM Tris/HCl pH 7.5, 1.4 M NaCl, 20 mM EDTA, CTAB 3 % [(w/v)]] and thereafter β -mercaptoethanol (final concentration 1.3%) were added to the samples. After 30 min at 60°C, one volume of chloroform/isoamyl alcohol (49:1) was added; the supernatant was recovered after centrifugation at 5,300 g for 15 min and precipitated with isopropanol at -20°C overnight. After centrifugation at 10,000 g for 15 min and washing with 0.2 M sodium acetate in 70% ethanol for 1 h at 4°C, RNA was dried and resuspended in RNase-free water and treated with 30 U of DNase I (Roche) for 15 min at 37°C.

Quality and quantity of RNA was verified using a NanoDrop® spectrophotometer ND-1000; the integrity was checked on agarose 0.8% gel electrophoresis. About 2–3 µg of total RNA was retro-transcribed using a cDNA Synthesis Kit (High Capacity RNA-to-cDNA kit, Life Technologies, Applied Biosystems) according to the kit instructions.

2.7 Quantitative real-time PCR (qPCR)

Different genes associated with a potential detoxification/homeostatic responses were assessed. In relation to metal chelation, the expression levels of METALLOTHIONEIN-LIKE PROTEIN 2A (*MET*), a gene encoded cysteine-rich protein with high metal-metal chelating capacity, was assessed. Associated with antioxidant metabolism, the genes studied were: L-ASCORBATE PEROXIDASE1 (*APX*), which catalyses the conversion of H₂O₂ into H₂O using ascorbate as electron donor, CATALASE (*CAT*), which catalyses the decomposition of H₂O₂, and a chloroplastic GLUTATHIONE REDUCTASE (*GR*), which promotes the reduction of glutathione disulfide (GSSG) to glutathione (GSH). Also, three genes involved in the epigenetic regulation of gene expression were assessed: CHROMOMETHYLASE3 (*CMT3*), involved in cytosine methylation of non-CG sites; DOMAIN REARRANGED METHYLASE2 (*DRM2*), associated to both the maintenance of non-CG methylation and *de novo* methylation in all sequence contexts; and REPRESSOR OF SILENCING 1 (*ROS1*), a 5-methylcytosine DNA glycosylase/lyase important for active DNA demethylation. Specific oligonucleotide primers were designed using PRIMER3 software (http://frodo.wi.mit.edu/cgi-bin/primer3/primer3_www.cgi, accessed 11 January 2006), according to Yokoyama and Nishitani (2001) and Applied Biosystem software. Each primer pair used was designed to obtain a final PCR product of approximately 110-170 bp length, and was tested for different parameters including robustness, successful amplification over a range of annealing temperatures, specificity and

the consistency of highly reproducible C_T values within the reactions of a triplicate. Primers for genes of interest were designed considering sequences from the seagrass EST database Dr. Zompo (Wissler et al. 2009) (<http://drzompo.uni-muenster.de/>). The reference gene *ELONGATION FACTOR (ELO_F)* was selected based on previous study by Ransbotyn and Reusch (2006). All primers used are listed in Table 1. qPCR was performed using a QuantStudio 12K Flex provided by Applied Biosystems in a 20 μ l total volume containing: 10 μ l 2x PowerSYBR Green PCR Master Mix (Applied Biosystems, Italy); 400 nM of each primer; and 30 ng cDNA. Reactions were performed in triplicate with the following cycles: 95°C for 10 min, 40 cycles of 95°C for 15 s and 60°C for 1 min. To test primer specificity, melting curve analysis (from 60°C to 95°C with an increasing heat rate of 0.5°C s⁻¹) was performed after amplifications. The calculations for determining the relative level of gene expression were made using the cycle threshold (C_T) value, according to the $2^{-\Delta\Delta C_T}$ method (Livak and Schmittgen 2001).

2.8. Statistical analysis

The data were tested for homogeneity of variance and normality and then subjected to one-way Analysis of Variance (ANOVA). Differences between individual means were determined from Tukey's *post hoc* multiple range test at 95% confidence interval using the software Origin Pro 8 (OriginLab).

3. Results

3.1 Photosynthetic performance

Compared to controls, there was a significant ($p < 0.05$) decrease in Fv/Fm under all Cd and Cu treatments, with exposure to Cu having a greater effect than Cd (Figure 1).

3.2 Metal accumulation

The concentrations of Cd and Cu in leaves increased significantly with increasing metal exposure; however, patterns differed when metals were applied singly or in combination (Figure 2). Typically, significantly more Cu than Cd was accumulated and significantly higher concentrations of both were accumulated when applied singly. For example, under high Cd or high Cu, the concentrations of the two metals were 59 and 360 nmol g⁻¹(DW), respectively. In contrast, under a combination of high Cd and Cu, only 47 and 293 nmol g⁻¹(DW), respectively, were accumulated.

3.3 Metal chelators

The production of all thiols (GSH and PC2, PC3, PC4 and PC5) was similarly dependent on the metal, the concentration and whether in combination or single exposure (Figure 3). For all thiols, their concentrations significantly increased with greater single and combined metal exposure, although when Cd and Cu were applied together, levels of all thiols were significantly higher than when exposing to the same concentrations of Cu or Cd alone. The only exception to the latter was PC2 at high Cd and low Cu, which presented no significant differences compared with high Cu (see Figure 3B). Moreover, levels of GSH and PCs were generally significantly higher when *Z. marina* was exposed to Cu than Cd, under the two concentrations of exposure for both metals, although in PC3 and PC5 levels of PCs were not significantly different between low Cu and low Cd alone (Figure 3C, 3E). Finally, it was observed that the different thiols decreased their concentration as their level of polymerization increased. For instance, the highest concentrations of GSH, PC2, PC3, PC4 and PC5 were detected at high Cd and Cu together, with concentrations of 1375, 280, 204, 63 and 30 nmol g⁻¹ FW (Figure 3).

Level of transcripts encoding *MET* were only significantly higher than the controls at high Cd, and at low and high Cu; these metal treatments also did not present significant

differences with each other (Figure 4). The expression of *MET* was not significantly different between controls compared with the treatments at low Cd and low Cd and Cu together. The only downregulation observed in *MET* was recorded under the combination of high Cd and Cu (Figure 4).

3.4 Antioxidant metabolism

There were different patterns in the expression of the studied antioxidant enzymes. For *GR*, there was observed downregulation compared to the controls under treatments low Cd, high Cd and low Cu; between these single metal treatments, the lowest expression was recorded at high Cd, although without significant differences with low Cd (Figure 5A). The highest upregulation of *GR* was observed at the high Cu treatment, followed by the treatment at high Cd and Cu together. Transcript levels of *GR* were not significantly different in relation to the controls at low Cd and Cu together. For *APX*, trends showed a concomitant increase in the expression, from low Cd, high Cd, low Cu to high Cu; the latter treatments showed the highest levels of expression (Figure 5B). Transcripts of *APX* displayed no significant changes for low Cd and Cu together, in relation to the controls (Figure 5B). At high Cd and Cu together, there was upregulation of *APX*, although with no significant differences with treatments at single low or high Cu (Figure 5B). The expression of *CAT* was not significantly different between treatments at low levels of Cd or Cu, with respect to controls (Figure 5C). There was significant upregulation of *CAT* at high Cd or high Cu, and even higher at low Cd and Cu together; however, the latter treatment did not show significant differences with at low Cd (Figure 5C). The highest levels of expression were observed at high Cd and Cu together (Figure 5C).

3.5 Epigenetic regulation of gene expression

Distinct trends in the expression of DNA methylation/demethylation-related genes were detected for different treatments (Fig. 6). Both *CMT3* and *DRM2* were significantly upregulated in all metal treatments, but the relative levels of expression did not follow the same patterns. For *CMT3*, the highest levels of expression were when exposed to Cu only, and then to Cd only; the lowest expression was observed when Cu and Cd were combined (Figure 6A). For *DRM2*, the highest level of expression was under high Cu, with intermediate overexpression in the combined treatments and lowest under low Cu and low and high Cd (Figure 6B). In contrast, there was downregulation of *ROS1* with exposure to Cd and to low Cu (Figure 6C). Only exposure to high Cu and to a combination of high Cd and Cu resulted in significant upregulation of this gene (Figure 6C).

4. Discussion

In this study, for the first time, we provide information on physiological and metabolic modifications in a seagrass species under both single and combined metal (Cd and Cu) exposure. More specifically, through the identification of treatment-specific patterns in photosynthetic performance, metal accumulation, thiols (GSH and PCs) production, and the expression of genes responsible for induction of metallothionein (MTs), antioxidant enzymes, as well as involved in DNA methylation/demethylation for modulating gene expression. We have gained a better understanding of the potential mechanisms involved in cellular detoxification and homeostasis that provides a degree of tolerance in this ecologically important seagrass species.

Under all single and combined metal treatments, levels of photosynthesis maximum quantum yield of PSII (Fv/Fm) decreased, although those containing Cu displayed more detrimental effects than when exposed only to Cd (except at low Cd and Cu together). It is known that excess Cd and Cu induce ROS over-production, especially in the chloroplast

(Fryzova et al. 2018), and it is very likely oxidative damage is responsible for the observed reduced photoinhibition of PSII under metal treatments. Since total accumulation of Cu was generally higher than that observed for Cd under all single and combined treatments; thus, it is reasonable that potentially less Cd bioavailability intracellularly caused smaller photoinhibition. Although it is known that Cd and Cu can target different components of PSII (Burda et al. 2003, Gonzalez-Mendoza et al. 2007), given the concentrations of exposure used in this study, metal-mediated photoinhibition seems to be principally induced upon concentrations of exposure and uptake.

It has been observed that *Z. marina*, as well as other seagrasses (e.g. *Cymodocea nodosa*, *P. oceanica*), preferentially accumulate Cd in leaves, whereas Cu accumulates in both leaves and roots (Lyngby and Brix 1984, Llagostera et al. 2011, Sanz-Lázaro et al. 2012). In our investigation, both Cd and Cu accumulation in the leaves of exposed plants increased with exposure dose, suggesting a good translocation to the aerial organs and/or increased direct uptake by leaves. The uptake of Cu was greater than Cd even if the levels of exposure to Cu, compared with those of Cd, were lower; the latter considering single and combined Cu and Cd treatments. In particular, while the accumulation of Cu increased proportionally to the Cu applied, in case of Cd it only increased 2.5 times when Cd exposure was 10 times greater (23 and 58 nmol g⁻¹ DW at 0.89 and 8.9 µM Cd, respectively). These results are in line with previous studies, which showed that Cu uptake compared with Cd in different tissues of *Z. marina* (leaves, rhizomes and roots) treated with increasing concentrations of these metals together of up to 50 µM (Lyngby and Brix 1982, 1984). A similar accumulation ratio between metals has been observed in the leaves of the seagrasses *C. nodosa* (Llagostera et al. 2011), *Thalassia hemprichii*, *Enhalus acoroides* and *Cymodocea rotundata* (Li et al. 2012). Interestingly, the concentrations of Cd and Cu accumulated

under combined metal treatments were lower than that under single metals treatment; a probable mechanism of metal competition for the binding site occurred (Foster et al. 2014). Taking into consideration the essential and non-essential role for plants of Cu and Cd, respectively, it is not surprising that their accumulation differed. Indeed, plants have several Cu-specific transporters (e.g. Atx1, Atox1, CUER, COPZ) (Ducic and Polle 2005), whereas Cd has complex uptake mechanisms though unspecific transporters (e.g. Fe transporters *IRT1* and *IRT2*) (Connolly et al. 2002, Nakanishi et al. 2006, Vert et al. 2009).

In this study the metal-complexing peptides GSH and PCs were detected in *Z. Marina*, using PCs with molecular structure $(\gamma\text{-Glu-Cys})_n$ gly of up to $n=5$ (PC5). *Z. marina* respond to Cd, Cu, and to a combination of these metals excess by inducing the synthesis of both, short (PC2-PC3) and long (PC4-PC5) chain PCs; however, the longer the PCs the less produced. In spite of the latter, it was generally shown that PCs induction was higher under Cd and Cu combined if compared with single metal treatments. It has been demonstrated that the level of polymerization of PCs has an important influence on metal tolerance; indeed, the longer the PC, the higher capacity will the species have to chelate and detoxify bioavailable metals (Clemens 2006). To the extent of our knowledge, records of PCs in seagrasses are restricted to the species *T. testudinum* and *E. acoroides*. While in *T. testudinum* PCs were detected as long as PC2 under Cd excess of up to 70 μM (Alvarez-Legorreta et al. 2008), in *E. acoroides* PCs were recorded with length of up to PC3 in Pb polluted sites (Nguyen et al. 2017). In spite of the scarce information that is available in this regard for seagrasses, records on other aquatic plants can provide insights on PCs-related induction under metal excess. For instance, Török et al. (2015) exposed the aquatic plants *Elodea canadensis*, *Salvinia natans* and *Lemna minor* to single Cd exposure of 818 mM , or

the latter combined with 260 mM Cu and 280 mM Zn, for 6 d. These authors observed that either under single Cd or Cd combined with Cu and Zn, the highest accumulation of these metals was observed in *L. minor*. Interestingly, only *L. minor* displayed PCs of up to PC7 under metal treatments, whereas *E. canadensis* and *S. natans* showed PCs only as long as PC3 (Török et al. 2015); it was also demonstrated that the activity of PCS was the highest in *L. minor* under control and metal treatments. Their data supports *L. minor* as metal, in particular Cd, Cu and Zn, tolerant species, also evidencing that PCs may have an important role in its metal tolerance strategies. Our results demonstrate, with up to PC5, that PCs are a relevant mechanism for the detoxification of bioavailable metals in *Z. marina*, also considering that levels of metal exposure in our study were considerable lower compared with those used, for instance, by Alvarez-Legorreta et al. (2008) and Török et al. (2015). It is also important to mention that our records constitute, for the first time, evidence of a seagrass species capable of synthesizing highly polymerized PCs of up to PC5 under metal excess.

METs are cysteine-rich proteins first described as metal-chelators, although it has been proven that their cysteine residues have also high ROS scavenging capacity to counteract oxidative stress and damage (Kumari et al. 1998). In seagrasses, the induction of METs under metal excess has been only assessed in *P. oceanica*, which showed the expression of 10 different METs under 1 μ M Cu or 10 μ M Cd for 2 d (Cozza et al. 2006), although the levels of transcripts were not quantified. Despite this information, MET coding genes have been also previously detected in *Z. marina* under high temperatures (Reusch et al. 2008) and increased salinities (Kong et al. 2013), likely to be induced to counteract oxidative stress. Our results demonstrate upregulation of *MET* only under single treatments of high Cd, and at low and high Cu. Interestingly, when metals were combined the levels of

expression were no different from the controls, in case of at low Cd and Cu, or down regulated, for high Cd and Cu. Even though the expression of this *MET* suggest its participation in Cd and Cu detoxification/homeostasis at least under single treatments, further research is necessary to address for its role as metal chelator and/or ROS scavenger. Moreover, considering that *Z. marina* encodes 10 different *MET* isoforms (see genome at <http://bioinformatics.psb.ugent.be/orcae/overview/Zosma>), it is very likely that other METs play different roles in detoxification and homeostatic control of metal excess, but this requires further investigation.

With regard to the reactive oxygen metabolism, *Z. marina* under Cd and/or Cu excess displayed enhanced antioxidant defences, manifested in increased production of GSH and higher expression levels of *GR*, *APX* and *CAT*, albeit to different extents depending on the metal, their concentration and whether single or combined exposure. However, there are common patterns showing that enhanced antioxidant defences were activated under high Cu, when supplied alone but also when combined with high Cd, and to lesser extent on exposure to only Cd. GSH trends are in agreement with those observed in *T. testudinum*, which displayed higher GSH content under Cd of up to 70 μ M for 6 d (Alvarez-Legorreta et al. 2008). As far as we are aware, there are no published data on the expression of *GR*, *APX* and *CAT* under metal stress in seagrasses, although the activity of CAT has been shown to increase proportionally with Cu exposure of up to 50 μ M, but not under Cd concentrations also of up to 50 μ M (Lin et al. 2016). Also, from research on terrestrial plants species there is evidence for the expression and activities of enzymes associated with antioxidant metabolism (e.g. *GR*, *APX* and *CAT*), to change under Cd and/or Cu exposure (e.g. Shah et al. 2013, Shahabivand et al. 2016, Kisa 2017, Yadav et al. 2018). An interesting feature is that the expression of *GR* in *Z. marina* did not follow the same

patterns as GSH production, especially under single Cd or Cu treatments; thus, the information suggests that other *GR* isoforms may be acting, part of GR activity is not transcriptionally regulated, and/or the *de novo* pathway ending in the activity of glutathione synthase (GS) is also participating in the restoration of GSH in *Z. marina*. Further investigation considering also *de novo* GSH synthesis under Cd and/or Cu excess may help disclosing these assumptions.

DNA hypermethylation plays a major role in modulating gene expression and it is considered an efficient protective mechanism to maintain genome integrity against homologue recombination and unwanted transposition that could be enhanced by abiotic stressors (Bender 1998, Bilichak et al. 2012). In *Z. marina*, both metals induced the overexpression of the DNA methyltransferases *CMT3* and *DRM2*, but to different magnitudes, which could suggest metal-specific methylation strategies. In line with these results, it has been demonstrated that *de novo* DNA hypermethylation is directly correlated with the upregulation of *CMT1* in *P. oceanica* up to 50 μM Cd for as long as 4 d (Greco et al. 2012). Similar results were obtained when analysing the expression of several DNA methyltransferases, including *DMT1-2* and *CMT3-2*, in rice plants after exposure to 1 μM Cu and 10 μM Cd for 7 d, a feature inherited in subsequent progeny (Ou et al. 2012). Furthermore, in *H. verticillata* treated with 0.16 μM Cu for 5 d there was increased production of four proteins with DNA methyltransferase activity, which was reflected later with hypermethylation of genomic DNA (Shi et al. 2017). However, in the same study, Cu in excess of 1.6 μM triggered DNA demethylation as a consequence of Cu-mediated oxidative stress (Shi et al. 2017). Interestingly, in our study, the 5-methylcytosine DNA glycosylase *ROS1* involved in DNA demethylation was downregulated after treatments at low and high Cd, and at low Cu, whereas it was overexpressed in treatments containing

high Cu, even when combined with Cd; thus, similar to the observations on *H. verticillata*, up-regulation of *ROS1* could be a direct consequence of an oxidative stress condition induced by these metal treatments. In addition, the overexpression of *ROS1* and consequently DNA hypomethylation could allow the selective expression and activation of genes involved in stress response and tolerance, as it was observed with *GR*, *APX*, and *CAT*.

5. Conclusion

The seagrass *Z. marina* exposed to Cd and/or Cu excess demonstrated interdependent physiological, metabolic and transcriptomic responses. The seagrass showed to be biologically viable within the range of Cd and Cu concentrations applied in this study, when exposed singly and in combination treatments, which was observed in terms of their photosynthetic performance. Metal accumulation and the activation of intracellular defences demonstrated increased intracellular metal concentrations in *Z. marina*, under single and combined treatments. Specifically, intracellular metal homeostasis and detoxification of the metals involved the induction of GSH, PCs and METs, the expression of antioxidant enzymes and the activation of methylation/demethylation pathways of gene regulation. This represents the first investigation at different levels of biological organization on seagrasses under combined metal exposure, providing insights of their physiological and metabolic strategies in order to cope with metal-mediated stress in polluted environments.

6. Acknowledgements

The research was funded by a fellowship granted by the European Cooperation in Science Technology Cost Action ES0906 to M. Greco. C.A. Sáez was funded by projects FONDECYT N°11160369 and INACH RT_09_16.

7. References

- Aina, R., S. Sgorbati, A. Santagostino, M. Labra, A. Ghiani, and S. Citterio. 2004. Specific hypomethylation of DNA is induced by heavy metals in white clover and industrial hemp. *Physiologia Plantarum* **121**:472-480.
- Alvarez-Legorreta, T., D. Mendoza-Cozatl, R. Moreno-Sanchez, and G. Gold-Bouchot. 2008. Thiol peptides induction in the seagrass *Thalassia testudinum* (Banks ex Konig) in response to cadmium exposure. *Aquatic Toxicology* **86**:12-19.
- Ambo-Rappe, R., D. L. Lajus, and M. J. Schreider. 2011. Heavy metal impact on growth and leaf asymmetry of seagrass, *Halophila ovalis*. *Journal of Environmental Chemistry and Ecotoxicology* **3**:149-159.
- Bartels, A., Q. Han, P. Nair, L. Stacey, H. Gaynier, M. Mosley, Q. Q. Huang, J. K. Pearson, T.-F. Hsieh, and Y.-Q. C. An. 2018. Dynamic DNA methylation in plant growth and development. *International Journal of Molecular Sciences* **19**: 2144.
- Barwick, M., and W. Maher. 2003. Biotransference and biomagnification of selenium copper, cadmium, zinc, arsenic and lead in a temperate seagrass ecosystem from Lake Macquarie Estuary, NSW, Australia. *Marine Environmental Research* **56**:471-502.
- Bender, J. 1998. Cytosine methylation of repeated sequences in eukaryotes: the role of DNA pairing. *Trends in Biochemical Sciences* **23**:252-256.
- Bilichak, A., Y. Ilnystkyy, J. Hollunder, and I. Kovalchuk. 2012. The progeny of *Arabidopsis thaliana* plants exposed to salt exhibit changes in DNA methylation, histone modifications and gene expression. *PLoS ONE* **7**:e30515.
- Bostrom, C., S. Baden, A. C. Bockelmann, K. Dromph, S. Fredriksen, C. Gustafsson, D. Krause-Jensen, T. Moller, S. L. Nielsen, B. Olesen, J. Olsen, L. Pihl, and E. Rinde.

2014. Distribution, structure and function of Nordic eelgrass (*Zostera marina*) ecosystems: implications for coastal management and conservation. *Aquatic Conservation-Marine and Freshwater Ecosystems* **24**:410-434.
- Boyko, A., and I. Kovalchuk. 2008. Epigenetic control of plant stress response. *Environmental and Molecular Mutagenesis* **49**:61-72.
- Burda, K., J. Kruk, G. H. Schmid, and K. Strzalka. 2003. Inhibition of oxygen evolution in Photosystem II by Cu(II) ions is associated with oxidation of cytochrome b559. *Biochemical Journal* **371**:597-601.
- Clemens, S. 2006. Toxic metal accumulation, responses to exposure and mechanisms of tolerance in plants. *Biochimie* **88**:1707-1719.
- Cobbett, C., and P. Goldsbrough. 2002. Phytochelatins and metallothioneins: roles in heavy metal detoxification and homeostasis. *Annual Review of Plant Biology* **53**:159-182.
- Cobbett, C. S. 2000. Phytochelatins and their roles in heavy metal detoxification. *Plant Physiology* **123**:825-832.
- Coelho, F. J. R. C., A. L. Santos, J. Coimbra, A. Almeida, Â. Cunha, D. F. R. Cleary, R. Calado, and N. C. M. Gomes. 2013. Interactive effects of global climate change and pollution on marine microbes: the way ahead. *Ecology and Evolution* **3**:1808-1818.
- Connolly, E. L., J. P. Fett, and M. L. Guerinot. 2002. Expression of the IRT1 metal transporter is controlled by metals at the levels of transcript and protein accumulation. *The Plant Cell* **14**:1347-1357.
- Cozza, R., T. Pangaro, P. Maestrini, T. Giordani, L. Natali, and A. Cavallini. 2006. Isolation of putative type 2 metallothionein encoding sequences and spatial expression pattern in the seagrass *Posidonia oceanica*. *Aquatic Botany* **85**:317-323.

- Choi, C.-S., and H. Sano. 2007. Abiotic-stress induces demethylation and transcriptional activation of a gene encoding a glycerophosphodiesterase-like protein in tobacco plants. *Molecular Genetics and Genomics* **277**:589-600.
- Deckert, J. 2005. Cadmium toxicity in plants: is there any analogy to its carcinogenic effect in mammalian cells? *Biometals* **18**:475.
- Ding, H., J. Gao, C. Qin, H. Ma, H. Huang, P. Song, X. Luo, H. Lin, Y. o. Shen, and G. Pan. 2014. The dynamics of DNA methylation in maize roots under Pb stress. *International Journal of Molecular Sciences* **15**:23537-23554.
- Dittami, S. M., S. Heesch, J. L. Olsen, and J. Collen. 2017. Transitions between marine and freshwater environments provide new clues about the origins of multicellular plants and algae. *Journal of Phycology* **53**:731-745.
- Doyle, J. 1991. DNA Protocols for Plants. Pages 283-293 in G. M. Hewitt, A. W. B. Johnston, and J. P. W. Young, editors. *Molecular Techniques in Taxonomy*. Springer Berlin Heidelberg, Berlin, Heidelberg.
- Ducic, T., and A. Polle. 2005. Transport and detoxification of manganese and copper in plants. *Brazilian Journal of Plant Physiology* **17**:103-112.
- Feng, S. J., X. S. Liu, H. Tao, S. K. Tan, S. S. Chu, Y. Oono, X. D. Zhang, J. Chen, and Z. M. Yang. 2016. Variation of DNA methylation patterns associated with gene expression in rice (*Oryza sativa*) exposed to cadmium. *Plant, Cell & Environment* **39**:2629-2649.
- Ferrat, L., C. Pergent-Martini, and M. Roméo. 2003. Assessment of the use of biomarkers in aquatic plants for the evaluation of environmental quality: application to seagrasses. *Aquatic Toxicology* **65**:187-204.

- 523 Foster, A. W., D. Osman, and N. J. Robinson. 2014. Metal preferences and metallation.
524 Journal of Biological Chemistry **289**:28095-103.
- 525 Foyer, C. H., and G. Noctor. 2011. Ascorbate and glutathione: The heart of the redox hub.
526 Plant Physiology **155**:2-18.
- 527 Fryzova, R., M. Pohanka, P. Martinkova, H. Cihlarova, M. Brtnicky, J. Hladky, and J.
528 Kynicky. 2018. Oxidative Stress and Heavy Metals in Plants. Pages 129-156 in P.
529 de Voogt, editor. Reviews of Environmental Contamination and Toxicology
530 Volume 245. Springer International Publishing, Cham.
- 531 Giordani, T., L. Natali, B. E. Maserti, S. Taddei, and A. Cavallini. 2000. Characterization
532 and expression of DNA sequences encoding putative type-II metallothioneins in the
533 seagrass *Posidonia oceanica*. Plant Physiology **123**:1571-1582.
- 534 Gonzalez-Mendoza, D., F. E. Y. Gil, J. M. Santamaria, and O. Zapata-Perez. 2007.
535 Multiple effects of cadmium on the photosynthetic apparatus of *Avicennia*
536 *germinans* L. as probed by OJIP chlorophyll fluorescence measurements. Zeitschrift
537 Fur Naturforschung C-a Journal of Biosciences **62**:265-272.
- 538 Greco, M., A. Chiappetta, L. Bruno, and M. B. Bitonti. 2012. In *Posidonia oceanica*
539 cadmium induces changes in DNA methylation and chromatin patterning. Journal of
540 Experimental Botany **63**:695-709.
- 541 Greco, M., A. Chiappetta, L. Bruno, and M. B. Bitonti. 2013. Effects of light deficiency on
542 genome methylation in *Posidonia oceanica*. Marine Ecology Progress Series
543 **473**:103-114.
- 544 Guo, W.-J., M. Meetam, and P. B. Goldsbrough. 2008. Examining the specific
545 contributions of individual *Arabidopsis* metallothioneins to copper distribution and
546 metal tolerance. Plant Physiology **146**:1697-1706.

- Kalubi, K., M. Mehes-Smith, G. Spiers, and A. Omri. 2017. Variation in whole DNA methylation in red maple (*Acer rubrum*) populations from a mining region: association with metal contamination and cation exchange capacity (CEC) in podzolic soils. *Ecotoxicology* **26**:405-414.
- Kisa, D. 2017. Expressions of glutathione-related genes and activities of their corresponding enzymes in leaves of tomato exposed to heavy metal. *Russian Journal of Plant Physiology* **64**:876-882.
- Kong, F. N., Y. Zhou, P. P. Sun, L. M. Liu, and Y. X. Mao. 2013. Generation and analysis of expressed sequence tags from the salt-tolerant eelgrass species, *Zostera marina*. *Acta Oceanologica Sinica* **32**:68-78.
- Kumar, M., A. Bijo, R. S. Baghel, C. Reddy, and B. Jha. 2012. Selenium and spermine alleviate cadmium induced toxicity in the red seaweed *Gracilaria dura* by regulating antioxidants and DNA methylation. *Plant Physiology and Biochemistry* **51**:129-138.
- Kumari, M. V., M. Hiramatsu, and M. Ebadi. 1998. Free radical scavenging actions of metallothionein isoforms I and II. *Free Radical Research* **29**:93-101.
- Lavoie, M., S. Le Faucheur, C. Fortin, and P. G. Campbell. 2009. Cadmium detoxification strategies in two phytoplankton species: metal binding by newly synthesized thiolated peptides and metal sequestration in granules. *Aquatic toxicology* **92**:65-75.
- Leitenmaier, B., and H. Küpper. 2013. Compartmentation and complexation of metals in hyperaccumulator plants. *Frontiers in Plant Science* **4**:374.
- Li, L., X. Huang, D. Borthakur, and H. Ni. 2012. Photosynthetic activity and antioxidative response of seagrass *Thalassia hemprichii* to trace metal stress. *Acta Oceanologica Sinica* **31**:98-108.

- Li, Y., X. Chai, H. Wu, W. Jing, and L. Wang. 2013. The response of metallothionein and malondialdehyde after exclusive and combined Cd/Zn exposure in the crab *Sinopotamon henanense*. PLoS ONE **8**:e80475.
- Li, Y., S. Kumar, and W. Qian. 2017. Active DNA demethylation: mechanism and role in plant development. Plant Cell Reports:1-9.
- Li, Z., Z. Liu, R. Chen, X. Li, P. Tai, Z. Gong, C. Jia, and W. Liu. 2015. DNA damage and genetic methylation changes caused by Cd in *Arabidopsis thaliana* seedlings. Environmental Toxicology and Chemistry **34**:2095-2103.
- Lin, H. Y., T. Sun, Y. Zhou, and X. M. Zhang. 2016. Anti-oxidative feedback and biomarkers in the intertidal seagrass *Zostera japonica* induced by exposure to copper, lead and cadmium. Marine Pollution Bulletin **109**:325-333.
- Liu, Y., H. Wu, L. Kou, X. Liu, J. Zhang, Y. Guo, and E. Ma. 2014. Two metallothionein genes in *Oxya chinensis*: Molecular characteristics, expression patterns and roles in heavy metal stress. PLoS ONE **9**:e112759.
- Livak, K. J., and T. D. Schmittgen. 2001. Analysis of relative gene expression data using real-time quantitative PCR and the 2- $\Delta\Delta$ CT method. Methods **25**:402-408.
- Lukens, L. N., and S. Zhan. 2007. The plant genome's methylation status and response to stress: implications for plant improvement. Current Opinion in Plant Biology **10**:317-322.
- Lyngby, J. E., and H. Brix. 1982. Seasonal and environmental variation in cadmium, copper, lead and zinc concentrations in eelgrass (*Zostera marina* L.) in the Limfjor, k Denmark. Aquatic Botany **14**:59-74.
- Lyngby, J. E., and H. Brix. 1984. The uptake of heavy metals in eelgrass *Zostera marina* and their effect on growth. Ecological Bulletins **36**:81-89.

- 595 Llagostera, I., M. Pérez, and J. Romero. 2011. Trace metal content in the seagrass
596 *Cymodocea nodosa*: differential accumulation in plant organs. Aquatic Botany
597 **95**:124-128.
- 598 Macinnis-Ng, C. M., and P. J. Ralph. 2002. Towards a more ecologically relevant
599 assessment of the impact of heavy metals on the photosynthesis of the seagrass,
600 *Zostera capricorni*. Marine Pollution Bulletin **45**:100-106.
- 601 Macinnis-Ng, C. M., and P. J. Ralph. 2004. Variations in sensitivity to copper and zinc
602 among three isolated populations of the seagrass, *Zostera capricorni*. Journal of
603 Experimental Marine Biology and Ecology **302**:63-83.
- 604 Maserti, B., V. Ferrillo, O. Avdis, U. Nesti, A. Di Garbo, A. Catsiki, and P. Maestrini.
605 2005. Relationship of non-protein thiol pools and accumulated Cd or Hg in the
606 marine macrophyte *Posidonia oceanica* (L.) Delile. Aquatic Toxicology **75**:288-
607 292.
- 608 Maxwell, K., and G. N. Johnson. 2000. Chlorophyll fluorescence—a practical guide.
609 Journal of Experimental Botany **51**:659-668.
- 610 Nakanishi, H., I. Ogawa, Y. Ishimaru, S. Mori, and N. K. Nishizawa. 2006. Iron deficiency
611 enhances cadmium uptake and translocation mediated by the Fe²⁺ transporters
612 OsIRT1 and OsIRT2 in rice. Soil Science & Plant Nutrition **52**:464-469.
- 613 Nguyen, X. V., K. H. Le-Ho, and J. Papenbrock. 2017. Phytochelatin 2 accumulates in
614 roots of the seagrass *Enhalus acoroides* collected from sediment highly
615 contaminated with lead. Biometals **30**:249-260.
- 616 Nordlund, L. M., E. W. Koch, E. B. Barbier, and J. C. Creed. 2016. Seagrass ecosystem
617 services and their variability across genera and geographical regions. PLoS ONE
618 **11**:e0163091.

- 619 Ou, X., Y. Zhang, C. Xu, X. Lin, Q. Zang, T. Zhuang, L. Jiang, D. von Wettstein, and B.
620 Liu. 2012. Transgenerational inheritance of modified DNA methylation patterns and
621 enhanced tolerance induced by heavy metal stress in rice (*Oryza sativa* L.). PLoS
622 ONE 7:e41143.
- 623 Pal, M., T. Janda, and G. Szalai. 2018. Interactions between plant hormones and thiol-
624 related heavy metal chelators. Plant Growth Regulation 85:173-185.
- 625 Park, H., P. J. McGinn, and F. M. Morel. 2008. Expression of cadmium carbonic anhydrase
626 of diatoms in seawater. Aquatic Microbial Ecology 51:183-193.
- 627 Ransbotyn, V., and T. B. H. Reusch. 2006. Housekeeping gene selection for quantitative
628 real-time PCR assays in the seagrass *Zostera marina* subjected to heat stress.
629 Limnology and Oceanography: Methods 4:367-373.
- 630 Reusch, T. B. H., A. S. Veron, C. Preuss, J. Weiner, L. Wissler, A. Beck, S. Klages, M.
631 Kube, R. Reinhardt, and E. Bornberg-Bauer. 2008. Comparative analysis of
632 expressed sequence tag (EST) libraries in the seagrass *Zostera marina* subjected to
633 temperature stress. Marine Biotechnology 10:297-309.
- 634 Romero-Puertas, M., J. Palma, M. Gómez, L. Del Rio, and L. Sandalio. 2002. Cadmium
635 causes the oxidative modification of proteins in pea plants. Plant, Cell &
636 Environment 25:677-686.
- 637 Roncarati, F., C. A. Sáez, M. Greco, M. Gledhill, M. B. Bitonti, and M. T. Brown. 2015.
638 Response differences between *Ectocarpus siliculosus* populations to copper stress
639 involve cellular exclusion and induction of the phytochelatin biosynthetic pathway.
640 Aquatic Toxicology 159:167-175.

- 641 Sandalio, L., H. Dalurzo, M. Gomez, M. Romero-Puertas, and L. Del Rio. 2001.
 642 Cadmium-induced changes in the growth and oxidative metabolism of pea plants.
 643 Journal of Experimental Botany **52**:2115-2126.
- 644 Sanz-Lázaro, C., P. Malea, E. Apostolaki, I. Kalantzi, A. Marín, and I. Karakassis. 2012.
 645 The role of the seagrass *Posidonia oceanica* in the cycling of trace elements.
 646 Biogeosciences **9**: 2497-2507.
- 647 Seth, C. S., T. Remans, E. Keunen, M. Jozefczak, H. Gielen, K. Opdenakker, N. Weyens, J.
 648 Vangronsveld, and A. Cuypers. 2012. Phytoextraction of toxic metals: a central role
 649 for glutathione. Plant, Cell & Environment **35**:334-346.
- 650 Shah, K., P. Singh, and S. Nahakpam. 2013. Effect of cadmium uptake and heat stress on
 651 root ultrastructure, membrane damage and antioxidative response in rice seedlings.
 652 Journal of Plant Biochemistry and Biotechnology **22**:103-112.
- 653 Shahabivand, S., H. Z. Maivan, E. Mahmoudi, B. M. Soltani, M. Sharifi, and A. A. Aliloo.
 654 2016. Antioxidant activity and gene expression associated with cadmium toxicity in
 655 wheat affected by mycorrhizal fungus. Zemdirbyste-Agriculture **103**:53-60.
- 656 Shi, D., K. Zhuang, Y. Xia, C. Zhu, C. Chen, Z. Hu, and Z. Shen. 2017. *Hydrilla*
 657 *verticillata* employs two different ways to affect DNA methylation under excess
 658 copper stress. Aquatic Toxicology **193**:97-104.
- 659 Shukla, U., J. Singh, P. Joshi, and P. Kakkar. 2003. Effect of bioaccumulation of cadmium
 660 on biomass productivity, essential trace elements, chlorophyll biosynthesis, and
 661 macromolecules of wheat seedlings. Biological Trace Element Research **92**:257-
 662 273.

- 663 Török, A., Z. Gulyás, G. Szalai, G. Kocsy, and C. Majdik. 2015. Phytoremediation capacity
664 of aquatic plants is associated with the degree of phytochelatin polymerization.
665 Journal of Hazardous Materials **299**:371-378.
- 666 Verbruggen, N., C. Hermans, and H. Schat. 2009. Mechanisms to cope with arsenic or
667 cadmium excess in plants. Current Opinion in Plant Biology **12**:364-372.
- 668 Vert, G., M. Barberon, E. Zelazny, M. Séguéla, J.-F. Briat, and C. Curie. 2009. *Arabidopsis*
669 IRT2 cooperates with the high-affinity iron uptake system to maintain iron
670 homeostasis in root epidermal cells. Planta **229**:1171-1179.
- 671 Wang, H., L. He, J. Song, W. Cui, Y. Zhang, C. Jia, D. Francis, H. J. Rogers, L. Sun, and P.
672 Tai. 2016. Cadmium-induced genomic instability in *Arabidopsis*: Molecular
673 toxicological biomarkers for early diagnosis of cadmium stress. Chemosphere
674 **150**:258-265.
- 675 Waycott, M., C. M. Duarte, T. J. Carruthers, R. J. Orth, W. C. Dennison, S. Olyarnik, A.
676 Calladine, J. W. Fourqurean, K. L. Heck, and A. R. Hughes. 2009. Accelerating loss
677 of seagrasses across the globe threatens coastal ecosystems. Proceedings of the
678 National Academy of Sciences **106**:12377-12381.
- 679 Wissler, L., E. Dattolo, A. D. Moore, T. B. Reusch, J. L. Olsen, M. Migliaccio, E.
680 Bornberg-Bauer, and G. Procaccini. 2009. Dr. Zompo: an online data repository for
681 *Zostera marina* and *Posidonia oceanica* ESTs. Database **2009**.
- 682 Yadav, P., R. Kaur, M. K. Kanwar, A. Sharma, V. Verma, G. Sirhindi, and R. Bhardwaj.
683 2018. Castasterone confers copper stress tolerance by regulating antioxidant enzyme
684 responses, antioxidants, and amino acid balance in *B. juncea* seedlings.
685 Ecotoxicology and Environmental Safety **147**:725-734.

- Yang, J., L. Liu, Y. Gong, D. Huang, F. Wang, and L. He. 2007. Analysis of genomic DNA methylation level in radish under cadmium stress by methylation-sensitive amplified polymorphism technique. *Journal of Plant Physiology and Molecular Biology* **33**:219-226.
- Yokoyama, R., and K. Nishitani. 2001. A comprehensive expression analysis of all members of a gene family encoding cell-wall enzymes allowed us to predict cis-regulatory regions involved in cell-wall construction in specific organs of *Arabidopsis*. *Plant and Cell Physiology* **42**:1025-1033.
- Yruela, I. 2005. Copper in plants. *Brazilian Journal of Plant Physiology* **17**:145-156.
- Zhao, F., R. Jiang, S. Dunham, and S. McGrath. 2006. Cadmium uptake, translocation and tolerance in the hyperaccumulator *Arabidopsis halleri*. *New Phytologist* **172**:646-654.
- Zheng, J., X. Q. Gu, T. J. Zhang, H. H. Liu, Q. J. Ou, and C. L. Peng. 2018. Phytotoxic effects of Cu, Cd and Zn on the seagrass *Thalassia hemprichii* and metal accumulation in plants growing in Xincun Bay, Hainan, China. *Ecotoxicology* **27**:517-526.

Figure 1: The maximum quantum yield (Fv/Fm) of leaves of *Zostera marina* exposed to one of 6 treatments for 6 d: control (no metals added), 0.89 μM Cd (0.89 Cd); 8.9 μM Cd (8.9 Cd); 0.8 μM Cu (0.8 Cu); 2.4 μM Cu (2.4 Cu); 0.89 μM Cd + 0.8 μM Cu (0.89 Cd + 0.8 Cu); and 8.9 μM Cd + 2.4 μM Cu (8.9 Cd + 2.4 Cu). Bars represent means \pm SD (n = 3). Different letters denote significant differences at 95% confidence interval ($p < 0.05$).

Figure 2: The total concentration of Cd and Cu accumulated in leaves of *Zostera marina* exposed for 6 d to: control (no metals added), 0.89 μM Cd (0.89 Cd); 8.9 μM Cd (8.9 Cd); 0.8 μM Cu (0.8 Cu); 2.4 μM Cu (2.4 Cu); 0.89 μM Cd + 0.8 μM Cu (0.89 Cd + 0.8 Cu); and 8.9 μM Cd + 2.4 μM Cu (8.9 Cd + 2.4 Cu). Bars represent means \pm SD (n = 3). Different letters denote significant differences at 95% confidence interval ($p < 0.05$); lower and uppercase letters represent differences in total Cd and Cu accumulation, respectively.

Figure 3: The concentrations of levels of glutathione (GSH. A), phytochelatin 2 (PC2, B), PC3 (C), PC4 (D) and PC5 (E) in *Zostera marina* exposed for 6d to: control (no metals added), 0.89 μM Cd (0.89 Cd); 8.9 μM Cd (8.9 Cd); 0.8 μM Cu (0.8 Cu); 2.4 μM Cu (2.4 Cu); 0.89 μM Cd + 0.8 μM Cu (0.89 Cd + 0.8 Cu); and 8.9 μM Cd + 2.4 μM Cu (8.9 Cd + 2.4 Cu). Bars represent means \pm SD (n = 3). Different letters denote significant differences at 95% confidence interval ($p < 0.05$).

Figure 4: Levels of expression of METALLOTHIONEINS (MET) in *Zostera marina* exposed for 6 d to: control (no metals added), 0.89 μM Cd (0.89 Cd); 8.9 μM Cd (8.9 Cd); 0.8 μM Cu (0.8 Cu); 2.4 μM Cu (2.4 Cu); 0.89 μM Cd + 0.8 μM Cu (0.89 Cd + 0.8 Cu);

and 8.9 μM Cd + 2.4 μM Cu (8.9 Cd + 2.4 Cu). Bars represent means \pm SD ($n = 3$). Different letters denote significant differences at 95% confidence interval ($p < 0.05$).

Figure 5: Levels of expression of chloroplastic GLUTATHIONE REDUCTASE (*GR*; A), ASCORBATE PEROXIDASE1 (*APX*; B) and CATALASE (*CAT*; C) in *Zostera marina* exposed for 6 d to: control (no metals added), 0.89 μM Cd (0.89 Cd); 8.9 μM Cd (8.9 Cd); 0.8 μM Cu (0.8 Cu); 2.4 μM Cu (2.4 Cu); 0.89 μM Cd + 0.8 μM Cu (0.89 Cd + 0.8 Cu); and 8.9 μM Cd + 2.4 μM Cu (8.9 Cd + 2.4 Cu). Bars represent means \pm SD ($n = 3$). Different letters denote significant differences at 95% confidence interval ($p < 0.05$).

Figure 6: Levels of expression of CHROMOMETHYLASE3 (*CMT3*; A), DOMAIN REARRANGED METHYLASE2 (*DRM2*; B) and REPRESSOR OF SILENCING 1 (*ROS1*; C) in *Zostera marina* exposed for 6 d to: control (no metals added), 0.89 μM Cd (0.89 Cd); 8.9 μM Cd (8.9 Cd); 0.8 μM Cu (0.8 Cu); 2.4 μM Cu (2.4 Cu); 0.89 μM Cd + 0.8 μM Cu (0.89 Cd + 0.8 Cu); and 8.9 μM Cd + 2.4 μM Cu (8.9 Cd + 2.4 Cu). Bars represent means \pm SD ($n = 3$). Different letters denote significant differences at 95% confidence interval ($p < 0.05$).

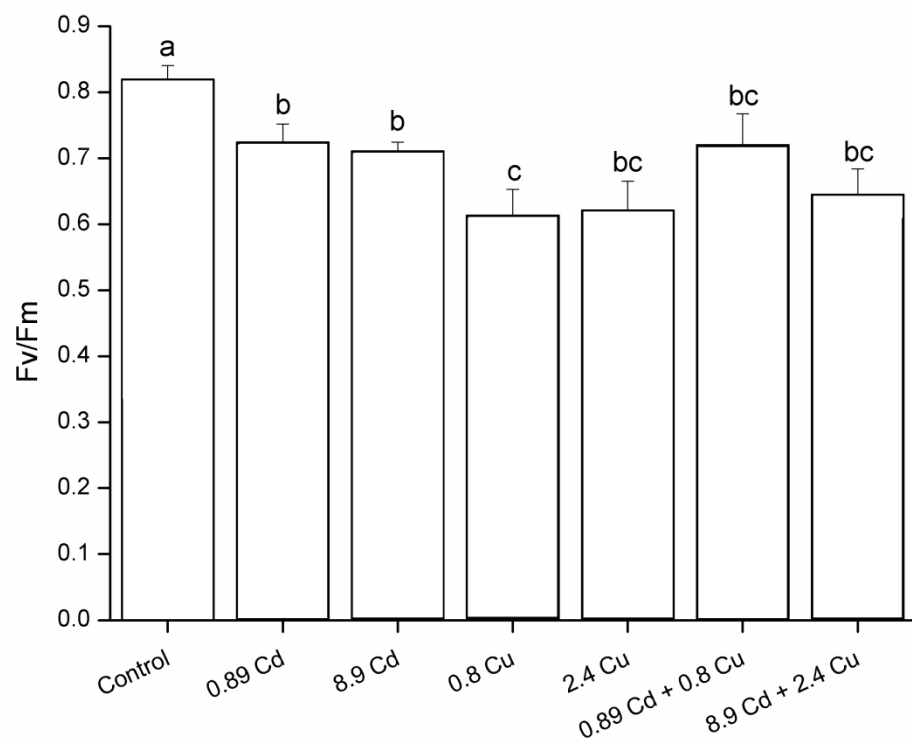


Figure 1

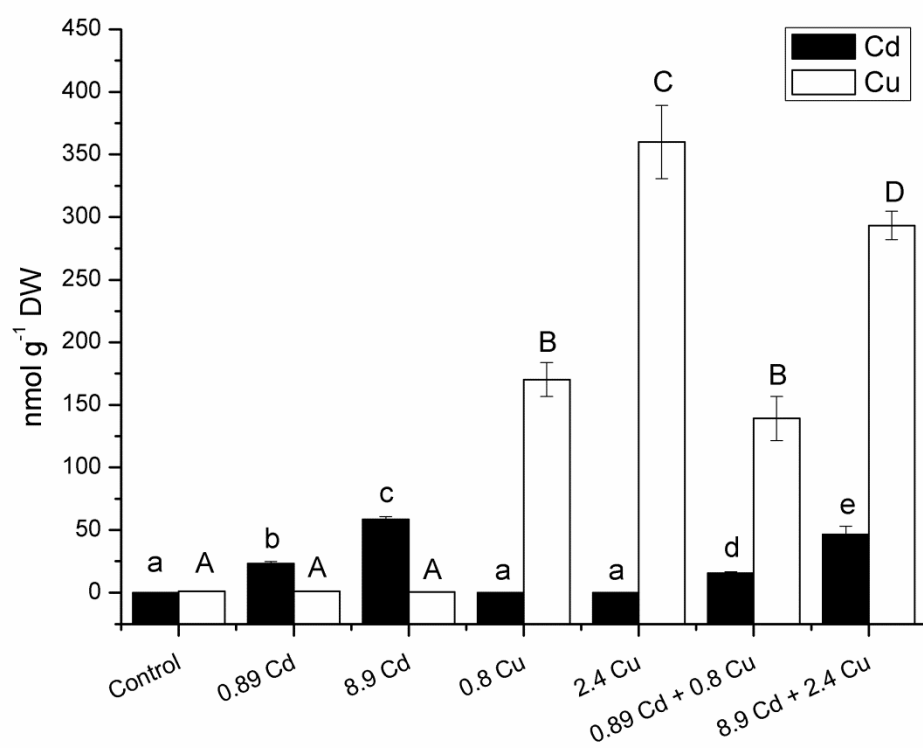


Figure 2

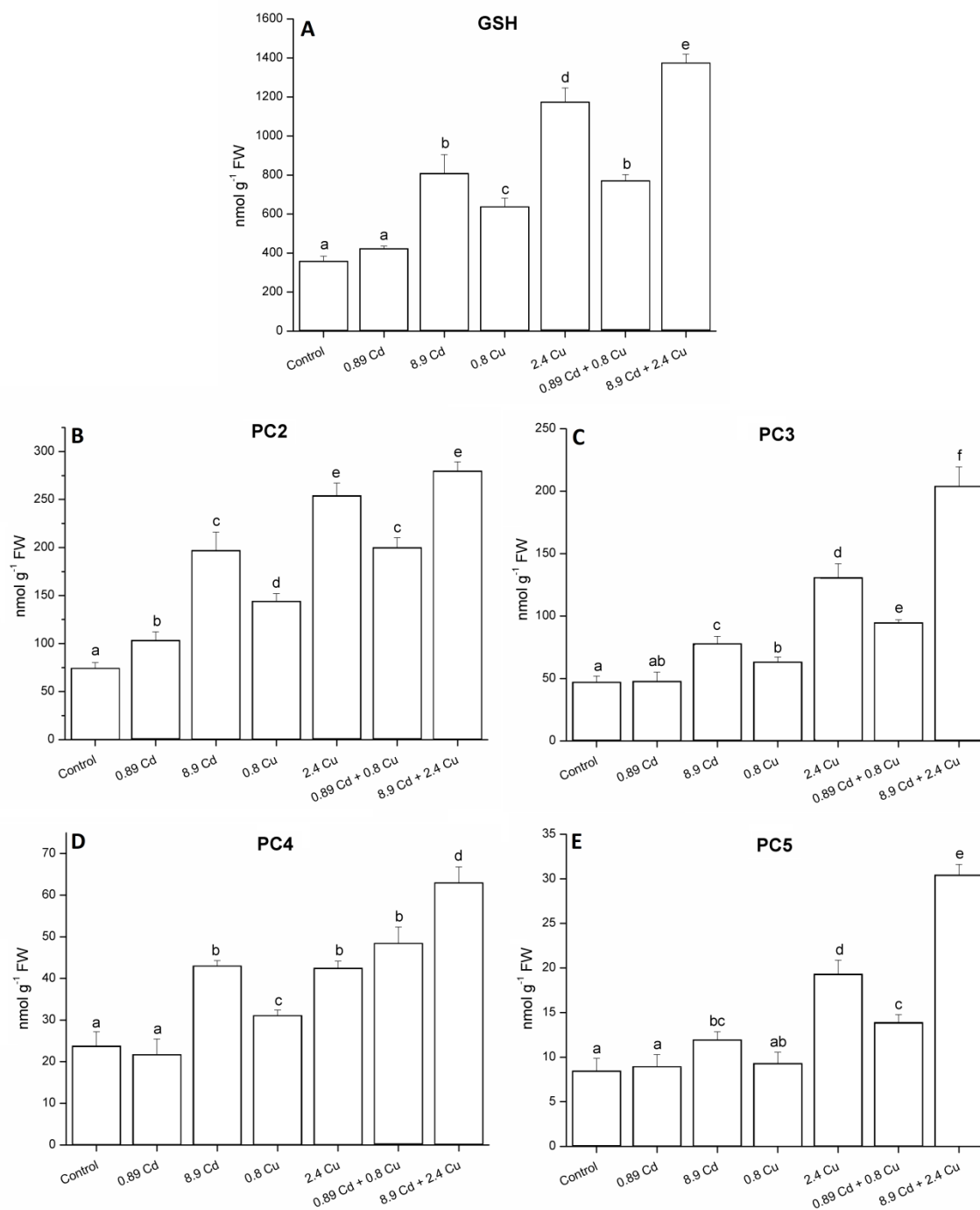


Figure 3

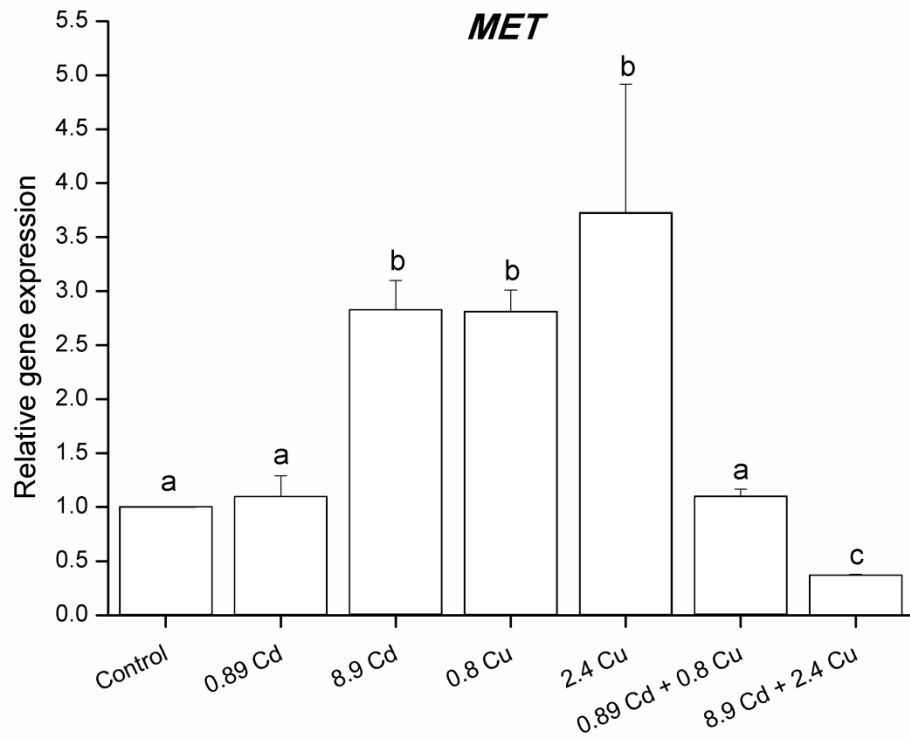


Figure 4

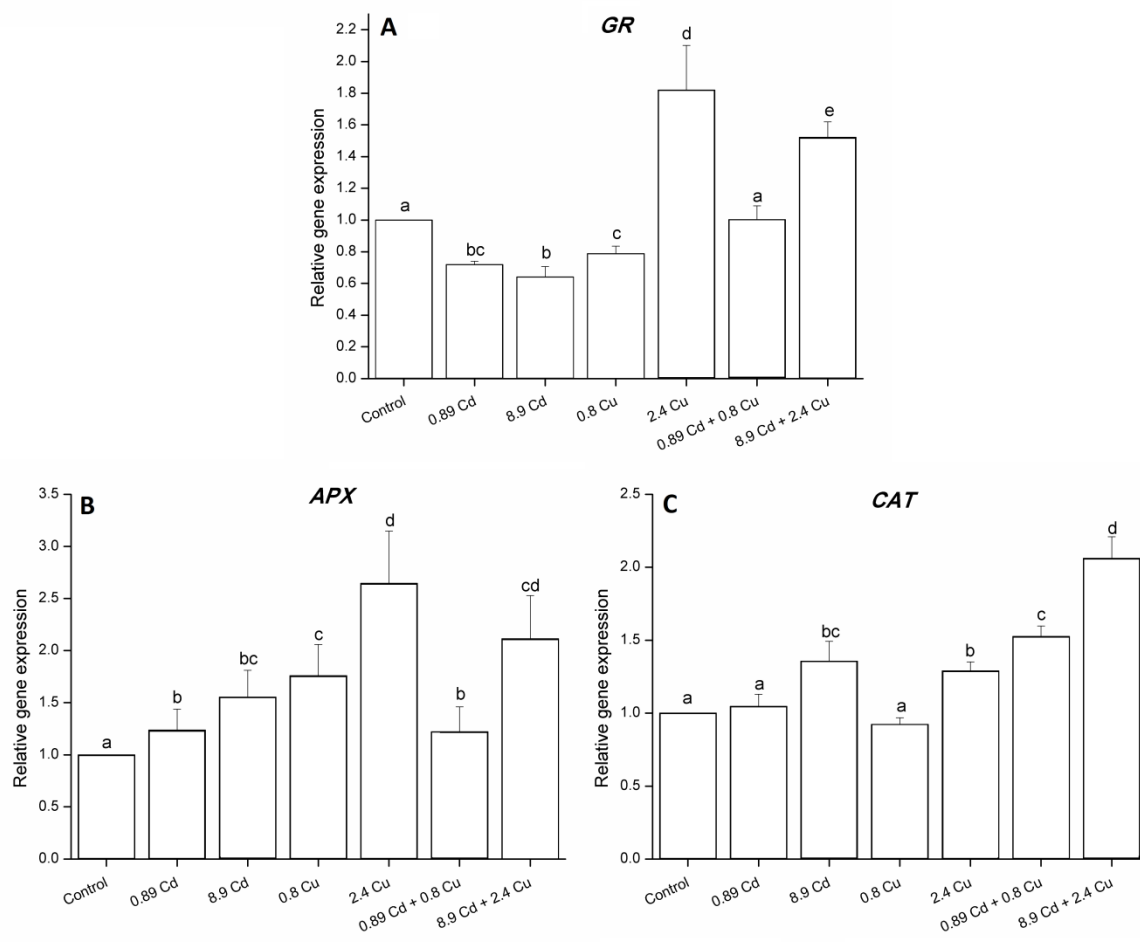


Figure 5

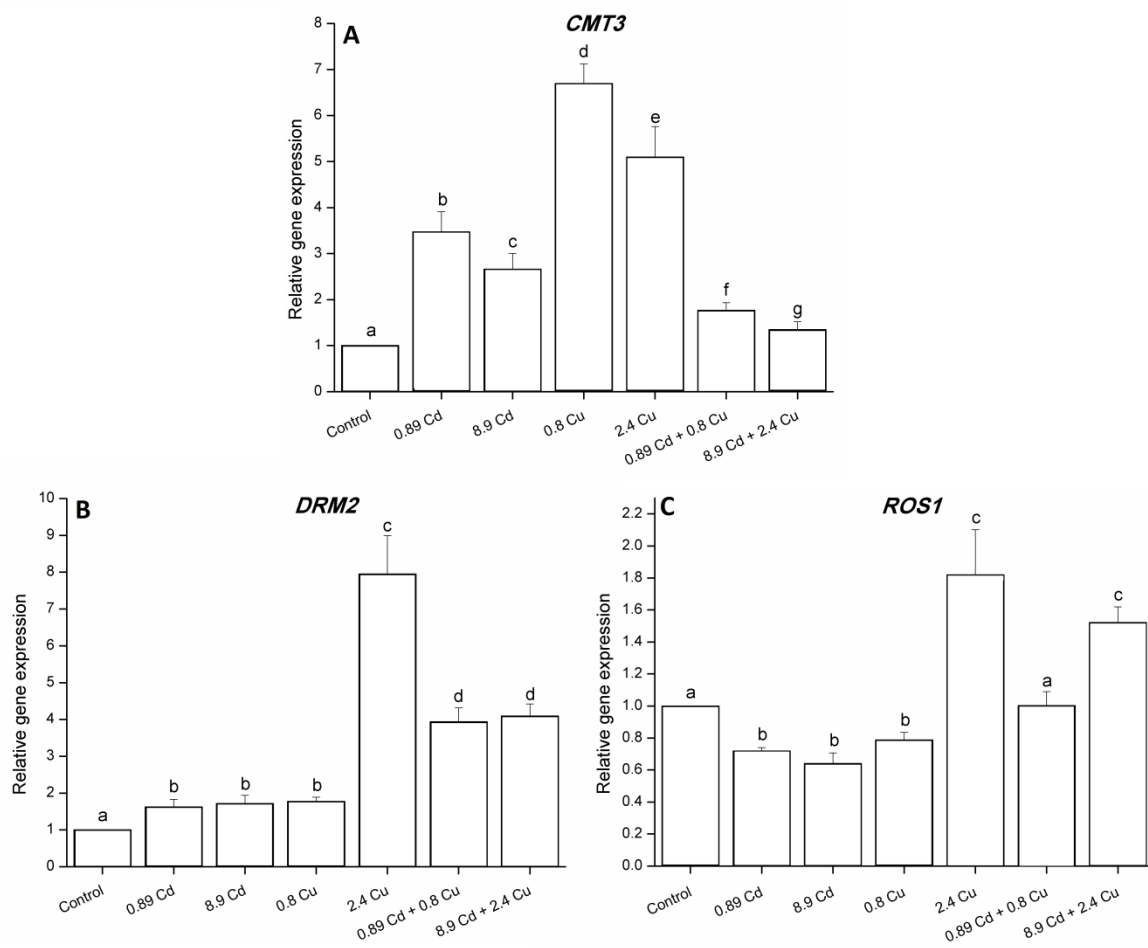


Figure 6

Cu accumulation is always higher than Cd, under single and combined treatments

GSH and PCs levels increased upon the accumulation of Cd and/or Cu

Zostera marina displayed up to PC5 under Cd and/or Cu exposure

Expression of *GR*, *APX* and *CAT* was the greatest under Cu, alone or combined with Cd

Expression of CMT, DRM2 and ROS1 showed epigenetic-mediated tolerance mechanisms

Table 1: list of primers used for qRT-PCR analyses on *Zostera marina*.

Primer sequences (5'-3')	Putative Genes ID	Accession Number
Primer Pair		
CCAGCAATGGCAGTTTCGT	<i>ELONGATION FACTOR</i>	AM268885
CAGATGGAACCGATGAGATTGA	<i>(ELO_F)</i>	
GATTTGCCTGGTCTTCGTGT	<i>CHROMOMETHYLASE3</i>	Q94F88
ACAGTTTCGTCCCACCAGAG	<i>(CMT3)</i>	
CCGATTAAGTCCAACCCAAA	<i>DOMAIN REARRANGED</i>	Q9M548
GAACGAATACGCCAACTGGT	<i>METHYLASE2 (DRM2)</i>	
TACCCAGCCCAGTCTAACGCA	<i>REPRESSOR OF SILENCING 1</i>	Q9SJQ6
GCCCCACCTGACAAAGTAAAGG	<i>(RSI)</i>	
GTGGAGGAAAGTGTGGGTGT	<i>METALLOTHIONEIN-LIKE</i>	P25860
TCACAGGGGAACTCCAGTC	<i>PROTEIN 2A (MT)</i>	
TTCAACCTGTTGGACGTCTG	<i>CATALASE (CAT)</i>	O24339
CGTTGAGTGTCGGCATAAGA		
ACAATCTTGCCACGACCTTC	<i>GLUTATHIONE REDUCTASE</i>	P80461
ATTGGGAGGTTCTCATGGC	<i>(GR)</i>	
ATCGGTCTGGTTTTGAAGGA	<i>L-ASCORBATE PEROXIDASE</i>	Q05431
TATCAACAAGAGGGCGGAAC	<i>1 (APX1)</i>	